Do Army Helicopter Training Simulators Need Motion Bases?

Michael E. McCauley
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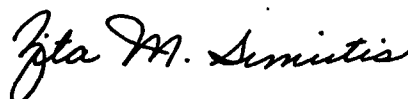United States Army Research Institute
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14. ABSTRACT *(Maximum 200 words)*:
This report reviews the arguments and the evidence regarding the need for simulator motion bases in training helicopter pilots. It discusses flight simulators, perceptual fidelity, history of motion bases, disturbance versus maneuver motion, human motion sensation, and reviews the empirical evidence for the training effectiveness of motion bases. The section on training effectiveness reviews research from relevant sources, including: Military helicopter, military transport, commercial airlines, general aviation, fighter, and attack aircraft. In addition the author describes a Perceptual Control Theory approach to determining the information requirements for simulator-based training. The author concludes that there is a substantial body of data to support the training effectiveness of flight simulation in general; that there is virtually no evidence to support the training effectiveness of motion platforms; that motion contributes to in-simulator performance, particularly for experienced pilots; that motion cues may be beneficial for flight training in unstable aircraft and in tasks involving disturbance cues, although the evidence is weak; and that motion, noise, and vibration contribute to the realism of the simulation and, therefore, strongly influence the acceptance of a simulator by the pilot community. There is no reliable evidence that a motion base prevents simulator sickness. Instructional design is more important than physical fidelity for training effectiveness.

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Do Army Helicopter Training Simulators Need Motion Bases?

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February 2006

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DO ARMY HELICOPTER TRAINING SIMULATORS NEED MOTION BASES?

EXECUTIVE SUMMARY

Research Requirement:

The issue of whether or not simulators for flight training need motion bases is a perennial one. It has recently re-emerged for the Rotary-Wing Aviation Research Unit (RWARU) of the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) at Fort Rucker, AL. Fort Rucker is the home of the U.S. Army Aviation Warfighting Center (USAAWC). USAAWC has embarked on its Flight School XXI training program. Among other innovations, the Flight School XXI program will enhance basic and advanced aviator training with additional simulator-based flight instruction. Hence, inquiries concerning the need of motion for simulator-based helicopter flight training have found their way to RWARU.

In addition, the issue of simulator motion has arrived anew with regard to the simulator-based training requirements for Future Combat Systems. Inquiries regarding this application also have found their way to RWARU. Thus, it was deemed appropriate by ARI to perform an up-to-date literature review on the subject.

Procedure:

An extensive literature review was commissioned by ARI. This review was to focus primarily on the specific need for motion in the simulator-based training of Army helicopter pilots. The central imperative, therefore, was to examine evidence from transfer of training experiments where motion was an independent variable. However, other related topics were reviewed as well, including: In-simulator learning; pilot preferences; force-cueing systems; simulator sickness; and Perceptual Control Theory.

Findings:

There is a substantial body of scientific data to support the training effectiveness of flight simulation. Flight simulators are unquestionably valuable for safely accomplishing training. However, there is virtually no scientific evidence to support the effectiveness of motion platforms for training. Motion does improve performance while in the simulator, particularly for experienced pilots. Motion cues may be beneficial under certain conditions, such as tasks involving disturbance motion, although the evidence for this is weak. Motion, noise, and vibration contribute to the realism, and therefore the pilot acceptance, of a simulator. Finally, there is no reliable evidence that a motion base prevents simulator sickness.

Utilization and Dissemination of Findings:

ARI's initial approach and early results were briefed to the Director, Directorate of Training Doctrine and Simulation, USAAWC, as well as to the Commander, Aviation Training Brigade, USAAWC. This final report represents RWARU's current understanding of this complicated issue, and will be made widely available to the simulation and training community at USAAWC.

DO ARMY HELICOPTER TRAINING SIMULATORS NEED MOTION BASES?

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DO ARMY HELICOPTER TRAINING SIMULATORS NEED MOTION BASES?

Introduction

Overview

The goal of this paper is to identify and summarize the arguments and evidence regarding the need for simulator motion bases in training U.S. Army helicopter pilots. For nearly 100 years, flight simulators have been used for pilot training. The motion base debate is nearly of equal length.

A brief background and history of the use of simulator motion bases in aviation training will be provided. The empirical evidence for the training effectiveness of motion bases will be reviewed, and other motion cueing devices will be mentioned. Research issues will be identified regarding the use of motion in helicopter pilot training. A recommendation is made for a new perspective on this issue based on Perceptual Control Theory.

Although Army helicopter training is the application of concern, evidence regarding motion cues will be reviewed more broadly, across fixed-wing as well as helicopter and in both commercial and military aviation. This approach is intended to provide a broad background and context for interpreting evidence about the need for motion bases in Army helicopter pilot training.

Framework and Perspective

The value of simulator features depends on one's perspective and the purpose of the simulator. Schroeder (1999) defined flight simulators as an attempt to reproduce the pilot-vehicle behavior of actual flight on the ground reasonably and safely. Simulators are used for several purposes, the two major ones being training and research. "Do you need a motion base?" sounds like a yes or no question, but the issue is more complex. A better characterization of the question might be-- How do flight simulator motion requirements vary as a function of:

- Simulator purpose
- Aircraft type
- Pilot experience level
- Training objectives, maneuvers, and tasks
- Criteria (training transfer, in-simulator performance, or pilot acceptance)
- Budget for simulator acquisition and operations?

Training is the product of training simulators. Hence, a training effectiveness perspective is the logical choice for evaluating the features of a training simulator. Simulator features that provide positive transfer of training (ToT) to the aircraft have value in terms of achieving training objectives (effectiveness) and reducing the

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resources required to achieve criterion performance (efficiency). If the acquisition cost of these features is within reason (cost-benefit), then there is a strong case for including them in simulator training system acquisition.

Reliable and valid data are the product of research and development (R&D) simulators. The perspective of handling qualities R&D is to achieve the most precise and accurate representation of pilot-vehicle behavior in the simulator. Experienced test pilots are the appropriate test subjects for simulator research on handling qualities. Simulator motion bases enable better in-simulator performance by experienced pilots. Thus, a clear case can be made for procuring motion bases for simulators that will be used to do handling qualities research. But the technology features that enable better performance in the simulator do not necessarily contribute to training effectiveness. There are other types of R&D that do not require precision in the simulator, such as research on cockpit instrument design layout, manning and automation, training research, and crew coordination (cockpit resource management). It is not clear that a motion base is necessary for these research simulators.

User acceptance (pilot preference) is a third perspective on the value of simulator features. How much value should be placed on simulator features that are preferred by pilots but generate no measurable training effectiveness? This is a value judgment that is not amenable to empirical research but may be important to an acquisition program manager or a military commander responsible for training and readiness. If simulator operators/instructors and trainees are "the customers" of training simulators, shouldn't some consideration be given to providing a product that has features desired and valued by the customer?

The Federal Aviation Administration (FAA) has an alternative perspective on the criteria for choosing motion bases (Burki-Cohen, Soja, & Longridge, 1998). The FAA requires a 6 degree of freedom (DoF) motion platform for certification as a top-level (Level D) flight simulator. Without a motion platform, the FAA calls it a "training device" rather than a training simulator. The FAA takes the position that public safety requires nothing less than full physical fidelity:

> ... the use of flight simulators in air-carrier training and checking
> activities goes beyond the standard transfer-of-training
> paradigm. When used as a substitute for the aircraft, the
> evaluation of pilot performance in the device constitutes a
> determination of the readiness of the pilot to perform immediately
> in line operations involving the flying public. That is, unlike many
> classical transfer-of-training situations, the simulator–trained air-
> carrier pilot is expected to perform within satisfactory standards
> of proficiency in the aircraft from day one. Consequently, the
> simulator must be capable of supporting 100 percent transfer of
> performance to the aircraft. Anything less would compromise
> safety. The existing standards for full flight simulator

qualification, all of which entail a requirement for platform-motion cueing, have a twenty year record of meeting the requisite criterion for transfer of performance. In the absence of compelling evidence to the contrary, it is therefore prudent to maintain these standards in the interest of public safety. Regulatory authorities will therefore continue to require platform motion...(Burki-Cohen, et al., 1998, p. 296).

Rather than basing acquisition decisions on empirical data supporting positive transfer, the FAA assumes that a Level D motion platform is necessary until proven otherwise. This position is not amenable to empirical confirmation because it amounts to proving the null hypothesis. There are at least two possible downsides of the FAA position: (1) physical displacement limitations of motion systems mean that less than full fidelity will be provided for any unusual accelerations associated with equipment failures and emergency procedures, thus introducing the prospect of negative transfer of training to the aircraft; (2) the cost of Level D simulators is beyond the budget of small regional carriers, contributing to the difficult economic basis of the industry.

Flight Simulators

Purposes of Flight Simulation

Flight simulators have been used for over half a century to provide trainees with some aspects of the flight experience to aid in the acquisition of flying skills without leaving the ground. Huff and Nagel (1975) claim that the simulation of piloted flight is almost as old as the history of flight itself. In addition to their use in training, flight simulators also have been used for research on topics such as pilot-vehicle interface design, subsystems design and development, and handling qualities evaluation. A classic report by the National Academy of Sciences identified four fundamental purposes of simulation: (1) training; (2) systems and equipment design, development, test, and evaluation; (3) research on human performance; and (4) licensing and certification (Jones, Hennessy, & Deutsch, 1985).

Flight simulators, with and without motion bases (also called "motion platforms"), have been used in a wide range of aircraft types and applications including military fixed-wing, military helicopter, general aviation, and commercial aviation (Jones, et al., 1985; Kaiser & Schroeder, 2003; Moroney & Moroney, 1999; Rolfe & Staples, 1986; Roscoe, 1980).

Flight simulators create the illusion of flight by simulating equipment, tasks, and environments. Training simulators provide these capabilities for the purpose of accomplishing pilot or aircrew training without using the actual aircraft. The potential benefits of training simulators are cost savings, time savings, risk reduction, and efficiency (student throughput).

Often, operational and technical personnel express the opinion that **realism** is the most important characteristic of a simulator, but in many ways, it is departures from realism that make simulators worthwhile. Here are some unrealistic examples: We fly but don't burn fuel; we crash but are uninjured and don't bend metal; we can practice a flight segment or set of tasks repeatedly without flying into position; we can make it day or night, light or dark, good or poor visibility; we can replay an event to provide training feedback; we can pause in mid flight; we can invoke equipment failures or other emergency procedures without risk; we can fly in the desert, over water, over high mountains, in urban areas, and in geo-specific areas all on the same day; we can practice nearly 60 ship landings per hour. All of those valuable features and capabilities are departures from realism.

The training value of a simulator is, in large part, derived from the instructional design and content rather than from the simulation hardware and software that emulate the functionality of the aircraft. As Caro (1973) pointed out over 30 years ago, the training value of a simulator depends more on a proper training program than on its realism. This is a lesson that is still being learned.

In an analysis of simulation by the National Academy of Sciences, the number one conclusion was, "Physical correspondence of simulation is overemphasized for many purposes, especially training" (Jones, et al., 1985, p. 92). And further, "... the concern with fidelity should shift from what is technically feasible in a hardware sense toward achieving greater effectiveness and efficiency in terms of behavioral objectives."

Objective and Perceptual Fidelity

Objective fidelity in a simulator refers to the physical correspondence between the flight simulator and the aircraft. Presumably, engineering techniques can be applied to measure both the aircraft and the simulator, yielding an index of objective fidelity.

Perceptual fidelity refers to the relationship between a pilot's subjective perceptions of the simulator and the aircraft. It also refers to the comparative sets of pilot performance and control strategies in the simulator and the aircraft. The term "presence" from the realm of virtual environments (VE) is similar to the concept of perceptual fidelity in flight simulators. According to Sadowski and Stanney (2002), presence does not necessarily equate to better performance in the VE. Likewise, the relationship between perceptual fidelity and performance in the flight simulator has not been established.

The "fidelity wars" have been ongoing in flight simulation for decades. However, there is little evidence to support the common belief that more fidelity equates to better training. A cogent summary on this issue was given 20 years ago in the National Academy of Sciences report on simulation:

The purpose of a simulator is to provide the conditions, characteristics, and events present in the operational situation necessary for the learning of skills that will be performed with actual equipment... Two related principles derive from this premise. First, the characteristics and methods of using simulators should be based on their behavioral objectives. Second, physical realism is not necessarily the only or optimal means for achieving the behavioral objectives of simulation. Because the history of simulator development is characterized by striving for improved realism through the advancement of technology, it is easy to forget that the learning or performance— not physical duplication—is the primary goal. (Jones, et al., 1985, p. 28)

Brief History of Simulator Motion Platforms

Motion systems in support of training have been used since 1918 to provide from one to six DoF using various drive mechanisms including pneumatic bellows, cables, cascaded gimbals, large amplitude beams, centrifuges, hydraulic pistons, and electrical motors (Puig, Harris, & Ricard, 1978). Edwin Link developed the Link trainer during 1927 – 1929, adapting the pneumatic bellows concept from his father's pipe organ factory to generate pitch, roll, and yaw movements of the crew station. In 1934 the Army Air Corps began purchasing Link trainers (the "Blue Box") and in 1937 a Link trainer was delivered to American Airlines. During World War II, as many as 10,000 Link trainers were in use (Moroney & Moroney, 1999).

External scene visual display systems were based on model boards in the 1950s and computer image generation (CIG) systems were developed in the 1960s. Since the 1970s, the rapid expansion of computational power has enabled enormous advances in image systems, complex aircraft models, and motion control systems.

From approximately 1970 to 2000 the synergistic hexapod hydraulic system, based on the "Stewart" platform design, was the most common form of 6 DoF motion platform (three angular—pitch, roll, and yaw; three linear—longitudinal, lateral, and vertical or heave axis). AGARD (1979; 1980) recommended that the following five characteristics be used to describe the dynamic capabilities of simulator motion platforms:

1. Excursion limits
2. Describing function
3. Linearity and acceleration noise
4. Hysteresis
5. Dynamic threshold
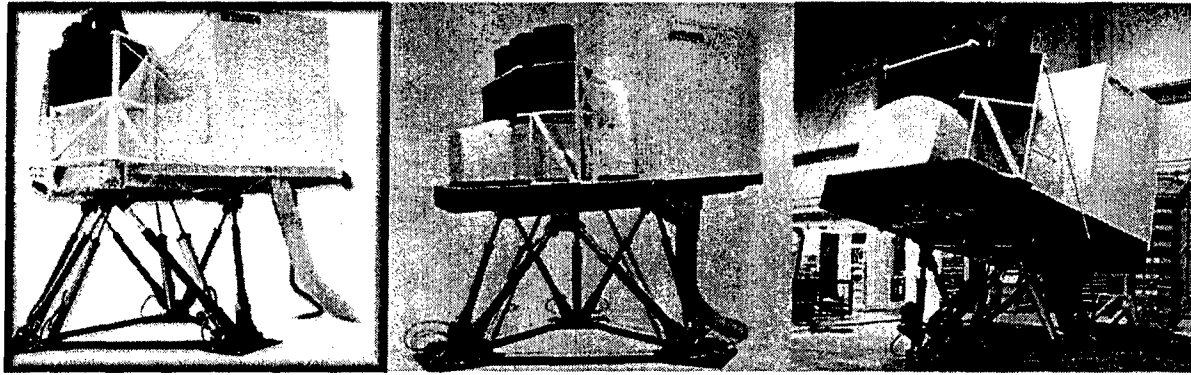
Figure 1. Examples of hexapod motion platforms (courtesy of Frasca International, Inc.).

Despite the increases in computational capability, motion platforms are not capable of achieving the sustained accelerations found in flight. To constrain a flight simulator to a building, motion cues must be of limited duration and amplitude. Thus, motion cueing systems provide brief onset cues followed by washout. Even the relatively large motion platforms used in Level D commercial aviation simulators have a limited range of linear displacement, on the order of 1-2 meters. For all but the most gentle, subtle, and short-lived maneuvers in flight (such as normal operations in a large commercial airliner), these constrained motion cues presented in the simulator depart, sometimes substantially, from the actual motion of the aircraft.

One new type of simulator, the centrifuge design, shown in Figure 2, can sustain a high level of acceleration. The primary axis can be varied according to the gimbal orientation. However, there is a possibility of negative transfer for scanning behavior with the centrifuge design because the trainee must maintain a fixed head position to avoid disorientation from vestibular Coriolis (Holly, 2004). It could be problematic for fighter pilots to learn to keep their head still.
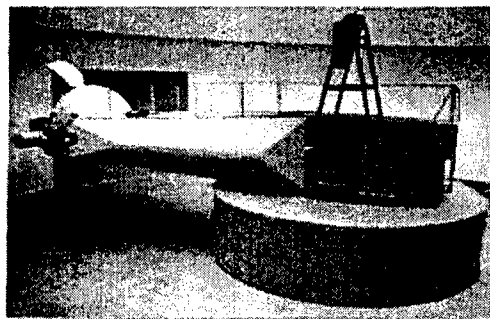
Figure 2. Wyle Dynamic Flight Simulator with dual gimbal gondola (courtesy of Wyle Laboratories, Inc.).

Motion bases come closest to matching normal operations in large commercial airplanes. They are least capable of matching high-level, sustained accelerations that characterize fighter and attack aircraft. Helicopter operations fall somewhere

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between those two extremes. Some individuals claim that motion cues are helpful for pilot training in unstable aircraft, such as helicopters (Kruk, 2004; Magee, 2004). This hypothesis has been confirmed for in-simulator performance, but has not been subjected to empirical test using the transfer of training paradigm.

The temporal characteristics of motion bases are important. Transport delay and cue asynchrony have been major issues in flight simulator design (Puig, et al., 1978). Due to the advances in computing power, those issues, while still important, have diminished. It is generally believed that transport delays and asynchronies must be limited to less than 150 or 200 ms. Due to computational power, current simulators are capable of less than 100 ms delay, which is thought to be below the threshold for the human user (Tsang & Vidulich, 2003).

The current trend in simulator motion systems is away from hydraulic toward electro-mechanical actuation. The payload of electrical systems must reach 18,000 kg to qualify for FAA Level D certification. However, some sources claim that electro-mechanical systems have challenges in the area of load capacity and velocity. At present, hydraulic systems appear to be the answer for those seeking payload of more than 18,000 kg or velocity greater than 1 m/s.

Disturbance versus Maneuvering Motion Cues

Gundry (1976) appears to have been the first to make a distinction between maneuver motion and disturbance motion. Maneuver motion arises within the pilot-vehicle control loop and results from pilot-initiated changes in the motion of the aircraft via the aircraft controls. Disturbance motion arises outside the control loop and results from turbulence, mechanical failure, or similar perturbations input to the aircraft that are unexpected by the pilot.

Gundry (1977) believed that simulator motion bases enabled pilots to respond more quickly and accurately to disturbance motion, thus leading to better performance in the simulator. Maneuver motion, on the other hand, does not provide an alerting function because it is pilot-initiated. Therefore, it may not contribute to improved performance in the simulator. Gundry did suggest, however, that for unstable aircraft, maneuver motion might contribute to pilots' flight control.

According to Caro (1979) all prior investigations of the ToT of simulator motion were performed with maneuver motion, ignoring the potential training value of disturbance motion. He suggested that disturbance motions might play an important role in alerting a pilot to the onset of turbulence or the failure of an aircraft component. Caro further distinguished between correlated and uncorrelated disturbance motion. Correlated disturbance motion is a consequence of events that are of immediate interest to the pilot and require his or her prompt attention, such as an asymmetrical external stores jettison. Uncorrelated disturbance motion does not alert the pilot to a disturbing event, but may be either regular, such as engine vibration, or irregular, such as turbulence. Caro suggested that motion may not be

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needed for stable aircraft or for maneuver motion, but that motion may contribute to training for unstable aircraft (or during unstable flight modes, such as approaching stall) or when disturbance motion cues are correlated with specific events related to training objectives. This suggestion implies that it is an instructional design decision, rather than an engineering decision, as to which specific disturbance cues should be included in the simulation. In short, Caro argued for a logical relationship between simulator motion and training requirements and, ultimately, for empirical test of the training effectiveness achieved by those logical analyses.

Research by Hosman and van der Vaart (1981) investigated the effect of visual and motion information on pilot performance in two types of roll control, a disturbance task and a compensatory tracking task. Three qualified jet transport pilots were tested in a simulator with a 3 DoF motion system (pitch, roll, and heave) and a visual system with both a central and peripheral display. The central display simulated an artificial horizon and the peripheral display was a checkerboard pattern provided by monitors fixed to the side windows of the flight simulator cabin. A quasi-random signal was input to the roll attitude of the simulated aircraft. In the disturbance condition, the roll input signal affected all pilot inputs, the two display systems and the motion system. In the tracking task, the roll input signal affected only the central display, providing a roll angle error. Both the peripheral displays and motion improved pilot control performance in both types of tracking tasks. The combination of peripheral and motion cueing led to the best performance. These results support the conclusion that simulator motion contributes to improved pilot performance in the simulator. Motion helps pilots counteract disturbance maneuvers in terms of increasing pilot gain, whereas the benefit with respect to tracking maneuvers is an increase in stability (reduced phase lag). These results do not, however, provide evidence of training transfer from the simulator to the aircraft.

How Do Humans Sense Motion?

Human orientation, head stabilization, postural control, and locomotion require information about the gravity vector plus body and head motion (Previc, 2004). Spatial orientation is a fundamental and primitive need for humans and we have evolved multiple, overlapping sensory mechanisms to accomplish the job, namely the visual, vestibular, and proprioceptive senses (Young, 2003). The ambient visual system, which is particularly strong in the peripheral retina, is the primary source of information for orientation and motion perception. Wide field of view visual systems that provide a coherent optical flow create a strong sense of "vection," the illusion of self-motion. According to Previc, the three major perceptual influences of ambient vision are on our sense of self-motion (vection), our perceived self-position in Earth-fixed space, and our perception of the slant and distance of the terrain around us. Visual information, unlike the vestibular system, does not habituate (decay over time) during constant-velocity motion. According to Previc, our perception of orientation and motion begins to break down without visual input. This is exemplified by circling behavior while walking blindfolded, velocity underestimations when pursuing a slowly moving target, and orientation misjudgments when we are tilted relative to gravity.

Simulator visual systems induce vection. In wide field of view visual systems, the illusion can be quite profound. Vection also is experienced in wide field of view entertainment media like an IMAX theatre or head-mounted VE display devices. When sitting in the IMAX theatre or in a fixed-base simulator, the input to the brain from the vestibular system is a loud and clear "static, no motion" signal. This creates a sensory conflict situation, i.e., the sensory input from the two information sources is no longer concordant and complementary. The solution, however, is not so simple as to provide motion cues via a motion base because motion bases are inherently limited in displacement and, in most flight maneuvers, are able to provide only onset cues, thus creating residual conflict with the visual input.

The vestibular system is an important source of information about body orientation and movement in the normal, on-ground environment. The semicircular canals and the otoliths constantly provide information about an individual's orientation relative to gravity and acceleration and velocity of the head in 6 DoF. The semicircular canals are quite sensitive, with a sensory threshold on the order of 0.1 degree/sec^2 (Young, 2003). Likewise, the otoliths can detect small changes in the gravity vector or sustained linear acceleration on the order of 5-10 cm/sec^2, or a head tilt of approximately 2 degrees. The vestibular system has been modeled thoroughly (Borah, Young, & Curry, 1979), although there are large individual differences and vestibular function is influenced by multisensory input, workload, attention, and other factors. According to Cheung (2004), within a frequency range of 0.1 to 5.0 Hz, which corresponds to natural movements such as walking, running, and jumping, the activity of the input signals from the semicircular canals approximates head velocity.

The accuracy and reliability of the orientation sensory systems are significantly altered when exposed to unusual gravitointertial environments such as flight. Vestibular and proprioceptive information can no longer be relied upon. Consequently, all responsibility for acquiring reliable information depends on vision (Cheung, 2004).

Vestibular Perception and Motion Bases

Various researchers have sought to design simulator motion systems based on vestibular models (e.g., Bussolari, Young, & Lee, 1988). Engineering analyses have been ongoing for many years regarding human manual control and improvements to motion cueing algorithms, e.g., Baron (1988); Guo, Cardullo, Telban, Houch, and Kelly (2003); Hess (1990); Schroeder (1999).

According to Rolfe and Staples (1986), the maneuver cues in commercial aircraft are of relatively low frequency and can be provided visually. However, in marginally stable aircraft, the pilot must pay prompt attention to motion cues and the lead provided by the motion platform contributes to the pilot's ability to maintain control (Kaiser & Schroeder, 2003).

There is no question that the vestibular system is involved in sensing motion during flight. One important lesson that all aviators must learn, however, is to ignore or suppress vestibular sensory input and to "trust your instruments." This invites the question—do we need to simulate motion to learn to ignore the motion?

Motion platform washout algorithms attenuate the motion onset cues to keep the platform within displacement limits. In so doing, they generate accelerations opposite in sign to what would be occurring in a sustained maneuver in the aircraft. It is typically assumed that the washout motion is below the vestibular threshold of the pilot, but this assumption is not tested and is likely to be false for any vigorous maneuver. Although there have been several attempts to define flight simulator motion system design based on vestibular models, there is no clear path from vestibular stimulation to the training effectiveness of motion.

It is no wonder that pilot trainees learning to fly on instruments are told by flight instructors to "trust your instruments" (rather than your vestibular system). All military pilots have been exposed to unusual attitude training and exposure to information about disorientation and the "leans." In flight, it is not possible for a pilot to use vestibular information to know accurately his/her attitude or dynamic state.

Ecological Approach

Brown, Cardullo, McMillan, Riccio, and Sinacori (1991) collaborated in an attempt to define a new approach to motion cueing in flight simulation. This work resulted in a new framework for analyzing and characterizing motion information in flight and a "need-based" analysis of cues available to the pilot for aircraft control. Control systems theory was a foundation for their approach, combined with analysis of human perception of motion via various sensory systems, plus a determination of what motion cues are necessary for specific flight maneuvers. This work was a major contribution and an advancement of the distinction between maneuver cues and disturbance cues made earlier by Gundry (1976).

Empirical Evidence for the Training Effectiveness of Motion Bases

In this section, empirical evidence for training transfer will be reviewed by aircraft type. First, an introduction to the transfer paradigm is provided.

Transfer of Training Research is Difficult, Expensive, Dangerous, and Rare

ToT experiments in aviation are difficult, expensive, and sometimes dangerous. It is not surprising that they are rare. The typical procedure in a ToT analysis is to expose one or more groups to training in a simulator and subsequently measure performance in the aircraft. There are many variations on this theme, but the main one is to establish a basis for comparison by including a control group that does not receive simulator training at all. In an investigation of the effect of motion, experimental subjects (pilots or pilot trainees) are randomly assigned to one of two

(or more) groups—one group gets motion and the other does not (fixed-base condition). If, for example, after training in the assigned simulator condition, the motion group performs significantly better in the aircraft than the no-motion group, then the results support the claim of positive transfer of training of simulator motion. Roscoe (1980) described the basic principles of measuring training transfer and calculation of the Incremental Training Effectiveness Function (ITEF).

One difficulty commonly faced by the ToT researcher in military aviation is that a training transfer analysis will disturb the flow of students through the training pipeline. Obtaining approval from the training commander can be difficult when some trainees will be assigned to a control group that gets no training.

Measuring trainee performance typically is easier in the simulator than in the aircraft. The more expensive and complex the aircraft, the less likely that approval will be obtained to do transfer tests in the aircraft, particularly if they involve dangerous tasks such as recovery from unusual attitudes or nap of the earth (NOE) flight. There is an increased risk of losing the aircraft, the trainee, and the instructor in these circumstances. Finally, ToT studies can be costly if a large sample of trainees must be tested in the aircraft. This is particularly true for expensive, complex aircraft with high operational costs. Preliminary analysis of statistical power is important for ToT research so that an appropriate sample size can be determined (e.g., Boldovici, 1992)

For these reasons, ToT experiments are very rare and "pseudo-transfer" (sometimes called "quasi-transfer") studies are more common. Pseudo-transfer means that students are trained in the simulator under various conditions, such as with and without motion, and then tested in the simulator with motion. This technique avoids the cost and the danger associated with testing in the aircraft. For example, the operational cost of flying a 747-400 in a transfer experiment would be prohibitive. Analysis of the transfer of emergency procedures in the 747-400 could be dangerous. Most ToT studies have been done in general aviation aircraft or military training aircraft.

General principles are difficult to derive from transfer studies because they must choose specific values of variables such as instructional technique, trainee experience (e.g., initial, transition, or refresher training), aircraft type, aircraft mission, maneuvers, tasks, simulator features, simulator calibration, instructors, and the reliability and validity of the performance measures.

Semple et al. (1980) reviewed transfer studies that used subjective (instructor ratings) and objective (e.g., bombing accuracy) performance measures and found that the subjective measures failed to detect training transfer whereas the objective measures of performance on the same tasks demonstrated positive transfer. Bricston and Burger (1976) used both objective and subjective measures and found positive transfer for both types of measures, but the objective measures resulted in substantially higher positive transfer.

Reliability of the performance measures, whether objective or subjective, is essential (Bittner, Carter, Kennedy, Harbeson, & Krause, 1986). Similarly, analysis of statistical power is strongly recommended, but often overlooked, before undertaking studies of ToT. Adopting unreliable performance measures in a ToT analysis (thereby reducing the power of the statistical tests) is likely to waste resources and provide little hope of detecting positive transfer, even when it exists.

ToT studies have an often-overlooked temporal aspect related to learning curves and retention. A positive transfer effect can be transitory. It depends, in part, on the time and intervening experience between the training and the measurement of transfer performance. Consider, for example, a paradigm where we might test for the persistence of a transfer effect, by administering a daily test battery in the aircraft. It would be possible to detect a small, but statistically significant, transfer effect by using highly reliable performance measures, but the transfer effect could be washed out by the second day. Ultimately, decisions about simulator features and their value for training effectiveness must be considered in the context of cost-benefit as well as training transfer. Cost-benefit issues will not, however, be addressed in this paper.

Military Helicopter

Bray (1994), an expert in motion system engineering, suggested that simulator motion may be more beneficial in helicopter simulation than in transport aircraft simulation because control sensitivities are higher and stability is lower. However, studies of ToT in helicopters are extraordinarily rare.

McDaniel, Scott, and Browning (1983) evaluated the contribution of platform motion to training effectiveness in a Navy SH-3 helicopter simulator (Device 2F64C). Because previous ToT research studies had sometimes been criticized for using simulator motion platforms with excessive lags and less than design accelerations, McDaniel et al. instrumented the motion system platform and subjected it to regular testing by simulation system engineers during the ToT experiment.

Two primary measures were used as criteria for transfer: (1) the number of flight hours in the SH-3 Sea King aircraft required by each student to pass designated flight checks; (2) the number of training trials required to demonstrate proficiency for specific flight tasks. The 26 student pilots who served as subjects were recent graduates of undergraduate pilot training (UPT) and were designated Naval Aviators with instrument certification. The simulator did not have a visual system installed during this research. The motion platform was a 6 DoF synergistic hexapod. The training program had two stages. The A stage was primarily focused on transition training, aircraft operation, and emergency procedures while flying Visual Flight Rules. The B stage, done mostly under Instrument Flight Rules, focused on mission-oriented training in antisubmarine warfare and search and rescue. Both training stages involved time in the flight simulator and time in the aircraft. For the two stages combined, the pilot trainees received 24.0 hours in the

flight simulator (twelve 30-min sessions) and ten flights in the SH-3 aircraft for a total of 25 flight hours.

McDaniel et al., (1983) found no significant differences in pilot performance between the group trained with motion and the group trained without motion. Further analysis revealed that the motion condition variable contributed only 4% of the total variance in flight hours in the A stage and 7% in the B stage. Variables that were predictive of success in the aircraft were: (1) The number of training trials required to achieve proficiency in the simulator was positively correlated with the number of training trials required to attain proficiency in the aircraft (e.g., the students who were slow to learn in the simulator were slow to learn in the aircraft); (2) Instructor variability (grading leniency) was correlated with flight hours and the number of task trials required for the student; (3) Variability in flight scheduling was correlated with student success (i.e., students not receiving regularly scheduled training tended to progress more slowly); and (4) Pilot training grades were correlated with later success in the operational assignment (fleet readiness squadron).

Among the conclusions of McDaniel et al. (1983) were the following:

- Platform motion training in the simulator did not transfer to the aircraft
- An engineering assessment demonstrated that the motion platform was within design specifications.

Horey (1992) evaluated the contribution of motion cueing conditions to helicopter pilot performance in a CH-53E Super Stallion simulator (device 2F120). A new visual system, presumably of greater weight, was to be installed in a simulator upgrade program and the motion cueing capability was to be reduced by restricting the displacement of each of the hexapod legs by 50%. The question was whether this restricted motion cueing capability would have a negative influence on training or on simulator sickness. Flight instructors nominated four maneuvers most likely to benefit from motion cueing:

1. Automatic Flight Control System/Servos Off Flight
2. Tail Rotor Failure/Separation
3. Shipboard Landings
4. External Loads

A preliminary analysis of simulator motion system response in these four tasks determined that only the Tail Rotor Failure maneuver resulted in motion platform leg excursions beyond 50 percent of full range. Nevertheless all four maneuvers were used in the experiment. A pseudo-transfer design was used to determine the effect of motion fidelity on training effectiveness in the simulator. Twenty-four fleet (fully trained and qualified) pilots were assigned randomly to three motion groups: no motion, restricted motion, and full motion. The restricted motion condition was characterized by simulating the 50% reduction in hexapod leg displacement. The

pilot participants were not informed of the motion condition manipulation. They flew each maneuver three consecutive times. The maneuver sequence was counterbalanced within each motion condition. Several performance measures were defined for each of the four maneuvers. For example, the Tail Rotor Failure maneuver was assessed by the following three performance measures: vertical speed, pitch, and roll at impact.

Results from the Horey (1992) experiment showed that only 1 of the 11 performance measures was significantly ($p < .03$) affected by motion condition—roll at impact in the Tail Rotor Failure maneuver. The results showed greater roll error at impact for the motion condition compared to the no motion or restricted motion conditions. Performance was significantly worse in the full motion condition.

The only other statistically significant effect ($p < .001$) was an interaction between trials and motion condition for the "time to landing" performance measure in the Shipboard Landing maneuver. The data indicated that performance improved over the three trials for both the restricted and no motion groups, but there was no performance improvement in the full motion group.

There are two contrasting interpretations of this finding: (1) the full motion condition failed to contribute to performance improvement on this task and performance measure; or (2) the full motion condition enabled superior performance on this task from the beginning, so no further improvements were likely.

Horey (1992) generated composite scores for each maneuver using standard score transformations but found no significant main effects or interactions for trials or motion conditions. This supports the finding that there were no reliable performance differences among the motion conditions. Horey concluded that neither restricted motion nor full motion cueing led to better performance in the simulator than no motion. He suggested that, if the motion manipulation failed to show differences in the simulator, it would be very unlikely to produce reliable performance differences in transfer to the aircraft.

Horey (1992) also measured simulator sickness using the traditional symptom checklist to determine whether the full motion condition might result in less sickness relative to the restricted- or no-motion groups. Motion condition had no significant effect on simulator sickness total scores or subscale scores.

The U.S. Army Research Institute, Rotary Wing Aviation Research Unit, has performed ToT analyses in Army helicopter simulators, e.g., Stewart, Dohme, and Nullmeyer (2002). This series of experiments showed quantitative evidence of positive transfer on all maneuvers (takeoff to hover, hover taxi, hovering turns, hovering autorotation, normal takeoff, traffic pattern, normal approach, and landing from a hover). A seat-shaker and a 5 DoF motion base were included in the simulator, but these studies focused on overall transfer, not on the contribution of simulator motion to the training.

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Other discussions about the use of motion for helicopter simulation are available in Boldovici (1992), but they are based on opinion and conjecture rather than empirical data. The expert opinions collected in this report confirmed the lack of empirical evidence to support the training value of motion bases. The pitfalls of accomplishing good TOT research were identified, including limited statistical power and safety concerns for testing in the aircraft. Boldovici boldly proclaimed that user acceptance of the simulator is not a legitimate concern for motion base procurement in military simulators. This is a debatable position.

Military Transport or Other

Ryan, Scott, and Browning (1978, in Burki-Cohen, et al., 1998) analyzed transition training in a P-3 Orion simulator to the S-2 Tracker aircraft. It is unclear from the cited source why the authors chose to train in a P-3 simulator, which is a 4-engine turboprop aircraft, and test transfer to the S-2, a smaller 2-engine aircraft. Ryan et al. (1978) chose tasks that featured disturbance motion, such as asymmetric engine failure. The results of the transfer experiment indicated that the approach and landing performance in the aircraft was not significantly different for the groups trained in the simulator with and without motion. One specific task, engine abort on takeoff, seemed to benefit from motion in the simulator, but this advantage did not transfer to the aircraft. Although there was no evidence of a beneficial effect of motion from the TOT results, the pilots indicated by questionnaire that they strongly favored having the motion cues available.

Parris and Cook (1978) performed a quasi-transfer analysis of motion using the NASA Ames Flight Simulator for Advanced Aircraft (FSAA) configured to simulate a U.S. Air Force KC-135 aircraft. The FSAA was a large 6 DoF motion system (+/- 10 m longitudinal displacement) with a visual scene and audio cueing. The visual system was a model board with a color television camera mounted on a gantry that provided a collimated color image to the pilot and co-pilot stations in the FSAA cab. In this analysis, the motion system was operated in two configurations-- a full motion condition and a restrained motion condition, which was intended to represent the motion capability of a typical synergistic hexapod system. Thirty-six qualified KC-135 aircraft commanders with an average of 1500 hr flight time served as test subjects. The subjects were randomly assigned to one of four groups for orientation and training: CSI (no visual, no motion); CSV (visual system, no motion), CSM (limited motion system, no visual); and CSMV (limited motion and visual system). The transfer testing was done in the full motion plus visual system. The flight maneuvers were based on the perceived problem that shutting down an engine in the KC-135 is not allowed by the USAF, thereby limiting training opportunities in the aircraft. Four types of engine failures were simulated:

- Outboard engine prior to lift-off
- Outboard engine after lift-off
- Inboard engine prior to lift-off

- Inboard engine after lift-off

Preliminary data analysis led to the selection of five criterion measures: Initial reaction time, sum of control reversals, lift-off point, total integrated roll and yaw, and maximum yaw angle. The subjects performed 26 trials in the four training conditions and subsequently performed 10 trials in the full FSAA system capability (CSF) condition as a quasi-transfer test. Following each phase of the investigation, the subjects completed questionnaires concerning the quality of the simulation.

Results of the Parris and Cook (1978) experiment showed that the pilots rated the combination of visual system and full motion system highly. During the training trials, the pilots rated the visual plus motion condition highly "as a training device for outboard engine failures," but the motion system (without visual) received much lower ratings. It should be noted that the visual system used in this experiment was primitive in comparison to the high resolution CIG systems in today's simulators.

The performance parameters showed mixed results with the various simulator conditions. The authors showed performance curves, but did no statistical analyses. The only apparent outcome was that a visual system is necessary to keep the aircraft on the runway during takeoff, regardless of engine failures or whether or not there is a motion platform.

Civilian: Commercial Airlines

A series of studies was sponsored by the FAA from approximately 1997 – 2003 to provide an empirical basis for decisions about whether training simulators for regional airlines should be required to have the same Level D large, expensive motion base as the major carriers. There are cost implications for smaller, regional airlines to procure Level D flight simulators or to rent time from major airlines on these simulators. The combined issues of training effectiveness and affordability prompted this series of studies.

The first experiment in this series (Go, Burki-Cohen, & Soja, 2000; Longridge, Burki-Cohen, Go, & Kendra, 2001) addressed these issues: Are there any flight tasks for which a measurable difference in simulator training effectiveness can be found with and without platform motion? Does a wide field of view (FOV) visual display provide more effective motion cueing than platform motion? Are existing (FAA) platform motion qualification criteria optimal? Is there a relationship between pilot experience level and the effectiveness of platform motion for training?

This experiment used a FAA-qualified Level C simulator (a lower rating than Level D) of a 30-passenger, twin-turboprop aircraft. The simulator had a wide FOV, high-quality visual system, and a 6 DoF motion system. The motion platform featured a hydraulic, synergistic hexapod with legs capable of a 60 inch stroke. The experimental approach attempted to avoid criticisms of previous ToT studies by measuring both pilot input and response, testing maneuvers and pilots likely to

benefit from motion, preventing pilot and instructor bias, and ensuring sufficient statistical power (Go et al., 2000; 2003). Subjects were 42 crews of experienced airline pilots, half of whom were assigned randomly to a Motion group and half to a No-Motion group. In accordance with the pseudo-transfer design, final testing was done in the simulator with the motion on. The test maneuvers were variations of engine failure on take-off, satisfying objectives of tasks that are high gain, high workload, short duration, and include both maneuver and disturbance motion.

The results showed that simulator motion did not affect, in any operationally meaningful way, initial evaluation, training progress, or ToT (Go et al., 2000). Simulator motion also did not, in any consistent way, affect the pilots' perception of performance, workload, training, comfort in the simulator, or acceptability of the simulator. According to the authors, there remain the possibilities that the simulator motion system used in this experiment may not have been typical of other Level C simulators and that the level of lateral acceleration produced by this particular motion base as a consequence of simulated engine failure may not have been sufficient to act as an alerting stimulus to the pilot.

A follow-up experiment of the effects of a motion base on airline pilot training was done by Go et al. (2003) using the NASA B747-400 simulator at Ames Research Center. This experiment, in part, addressed a criticism of the prior research that the lateral acceleration motion cueing was attenuated. The NASA B747-400 simulator used in this research was FAA-certified Level D with hexapod actuators capable of a 54-inch stroke. The motion washout filters were tuned and adjusted to provide the best possible lateral and vertical translation cues.

Forty qualified B747-400 pilots, current airline Captains and First Officers, participated as subjects. They were assigned randomly to either the Motion or No-Motion simulator condition and flew the simulator in three phases: Evaluation, Training, and Quasi-Transfer. After practice in the first two stages, both motion groups were evaluated in the simulator with the motion platform on (a quasi-transfer design). Dependent variables were task-relevant measures of pilot-vehicle performance that were derived from over 100 variables recorded in the simulation. Four maneuvers were chosen to emphasize the need for motion, including maneuver and disturbance cueing, asymmetric high-gain maneuvers, and high workload. Examples of the required maneuvers are takeoff with engine failure, precision instrument approach, and sidestep landing. Pilots received one familiarization trial on each of the four maneuvers, then three practice trials on each maneuver, followed by the quasi-transfer test comprising two iterations of the four maneuvers.

Results indicated a significant difference of group (Motion compared to No-Motion) on 7 of the 17 dependent variables, although the magnitude of the differences was small. Post hoc analysis showed that the No-Motion group flew the landing maneuvers more precisely than the Motion group, but with less control input. This is a surprising result, because the typical finding is that motion supports in-simulator flight precision, especially with experienced pilots. This group effect

transferred to the quasi-transfer trials, meaning that the No-Motion group still flew more precisely and with less effort than the Motion group when the motion base was active. In contrast, the Motion group had a faster response time than the No-Motion group in the engine-out on takeoff maneuver, probably because the motion provided a disturbance cue. This difference in response time only emerged during the quasi-transfer stage, when both groups received motion cues.

Both the Motion and No-Motion groups showed improved flight performance over time, indicating a training effect. The differences were small, probably because the subjects were qualified, experienced pilots and because their training time was short—only three trials. For some maneuvers, there were subtle differences between the two motion groups with regard to control strategy. Pilot opinions expressed in the questionnaires indicated that motion did not affect their perception of the quality of the simulator.

Go et al. (2003) concluded that no benefit of motion was found for recurrent training. Based on their statistical analyses, they could have claimed that the No-Motion condition was better, at least on a minority of the dependent measures. The results suggest that, for a large commercial aircraft, training without motion helps pilots adopt a steady control strategy rather than over-reacting to motion cues.

General Aviation

In a classic ToT analysis by Koonce (1974, in Roscoe, 1980), three groups of Air Force pilots of varying levels of experience received two days of refresher training in instrument flight procedures using a Singer-Link GAT-2 simulator. Then they performed the same tasks in a Piper Aztec on Day 3. The three groups differed only in motion condition—one group had no motion, one group had sustained (no washout) motion, and the third group had motion with washout.

There were several key outcomes illustrated in this experiment: (1) the performance of all three groups improved over the two days of practice and training; (2) all three groups continued to improve on the third day (in the aircraft); (3) there was evidence, though not statistically significant ($0.10 > p > 0.05$), of an interaction between performance in the simulator and in-flight, where the no-motion group performed best. Koonce (1974, in Roscoe, 1980) concluded that simulator motion tends to increase the subjects' acceptance of the simulator, improve performance in the simulator, and reduce workload, but these benefits of motion in the simulator do not transfer to performance in the aircraft.

Another classic motion ToT experiment was performed by Jacobs and Roscoe (1980) at the University of Illinois Aviation Research Laboratory. Four groups of nine non-aviators (flight-naive subjects) received training in basic instrument flight skills. One group trained in the Piper Cherokee Arrow aircraft rather than the simulator. Three of the groups received training in the simulator, one group with normal washout banking motion, one group with no cockpit motion (fixed-base), and the

other group with the direction of the banking motion reversed half the time. One aspect of the results was particularly surprising—none of the subjects in the random reversal group commented, or seemed to perceive, that the roll motion was sometimes in the wrong direction. Results from the practice sessions indicated an interaction between the aptitude predictor score and motion condition. Students with high aptitude scores performed nearly equally under any motion condition. Students with low aptitude scores seemed to perform better with the normal washout motion than with either the random-direction or the no-motion conditions. Results from the transfer test to the aircraft indicated that performance was nearly equivalent for the normal motion and the no-motion groups. Performance of the random washout group was not quite as good, except for the high-aptitude students.

Both the Jacobs and Roscoe (1980) and the Koonce (1974, in Roscoe, 1980) studies were done with a very limited motion base capability. The results are not necessarily indicative of more capable motion base systems.

The generalization of empirical findings is always an issue. How meaningful are results from small motion bases on small civilian aircraft simulators to other types of aircraft? There is no simple answer. Overall, the evidence from all sources must be considered for their contribution to decisions about specific aircraft types, missions, maneuvers, and other application features.

Fighter and Attack

Martin and Waag (1978) performed a ToT experiment using the Air Force Advanced Simulator for Pilot Training (ASPT). Pilots were trained in the simulator, with and without 6 DoF motion, in basic contact, approach and landing, and aerobatic tasks. No information is available about the quality of the motion provided by the ASPT motion base. The authors reported that positive transfer occurred for both groups, but there were no significant differences between the motion and no-motion groups when tested in the T-37 aircraft.

Hagin (1976) used the ASPT to expose Air Force pilot trainees to simulator training with and without 6 DoF motion. Flight tasks included takeoff, landing, and overhead traffic pattern. Transfer tests in the T-37 aircraft showed no significant differences between the motion and no-motion groups. In a follow-up experiment (Hagin, 1976) trainees progressed through the entire T-37 syllabus in the ASPT simulator, with and without motion. Subsequent performance ratings in the aircraft found no differences in the performance of pilots trained with or without motion in the simulator.

Woodruff, Smith, Fuller, and Weyer (1976) used the ASPT and the T-37 aircraft in another transfer experiment and found no difference between the motion and no-motion groups in the time to reach criterion performance in either the simulator or the aircraft.

The U.S. Air Force Scientific Advisory Board (1976, in Semple, et al., 1980) reviewed the existing evidence on motion platforms for simulation and concluded as follows:

> Based on the motion, no motion studies and experiments which have been run to date, a convincing case cannot be made for either including or excluding platform motion in flight simulator for tactical fighters. ... in the absence of valid, reliable measures of pilot performance, any attempt to assess the effects of training in a simulator on that performance will be unsatisfactory. (in Semple, et al., 1980, pp. 138-139)

Martin (1981) summarized five experiments using the ASPT and one using the Simulator for Air-to-Air Combat (SAAC) and concluded that the data did not show positive transfer of training from a motion platform.

> The addition of task-correlated platform motion cueing results in negligible transfer of training for initial jet piloting skills ...Existing data do not support procurement of sophisticated six-post synergistic platform motion systems for pilot contact skill acquisition and existing simulators for pilot training possessing synergistic platform motion systems can be equally effective if the motion system is not used. Both of these outcomes would result in substantial cost savings. (Martin, 1981, p. 2)

Summary of Empirical Evidence for Motion

In many ways, little has changed in the quarter century since Paul Caro wrote, "Flight simulator motion has been demonstrated to affect performance in the simulator, but ... transfer of training studies have failed to demonstrate an effect upon in-flight performance" (Caro, 1979, p. 493).

In a summary of motion cue requirements for flight simulators, Rolfe and Staples (1986, p. 126) concluded that, while extensive data support the beneficial effects of motion on the manner in which a pilot controls his simulated aircraft, "there are almost no results from transfer of training experiments showing that simulator motion is an effective training aid for most flight conditions." Interestingly, they mentioned that the difficulties of conducting ToT studies make it probable that there never will be enough data from ToT studies to serve as the sole basis for a decision to provide inertial motion cues in a training simulator.

Other Analyses of Flight Simulator Motion

Hall (1989) analyzed the need for motion platforms in training simulators and the factors that should be taken into account when assessing their training value. He

offered a logical, reasoned argument for the benefits of platform motion under certain circumstances, namely, when:

- A relatively unstable aircraft is being simulated (e.g., a helicopter or VSTOL aircraft)
- The pilot must engage in high gain, high frequency, manual control
- Pilot control activity and workload need to be similar to the actual aircraft

Hall (1989) reviewed research that found pilot control activity to be more similar to that found in the aircraft when simulator motion is engaged. He suggested that it is reasonable to expect that similar pilot control activity in the simulator and the aircraft will contribute to good training transfer. Hall further suggested that the consistent failure to find positive TOT from motion might be due to inadequate motion systems used in the research. While this argument may have validity for research conducted prior to about 1980, more recent TOT evaluations have specifically analyzed and tuned the motion systems prior to data collection, e.g., Go, et al. (2003). Nevertheless, Hall's cogent arguments for the benefits of motion under certain conditions deserve further investigation via empirical TOT experimentation. We concur with his recommendation that the relationships among flight tasks, aircraft types, manual control activity, and motion cueing requirements would benefit from further research.

Heintzman, Middendorf, and Basinger (1999) analyzed the force cueing requirements for tactical combat training devices. This ambitious review summarized the history of motion cueing systems including motion platforms, dynamic seats, and other devices. Heintzman stated that current motion platforms and other force cueing devices are far superior to the systems that were in use nearly 25 years ago when the Air Force decided to remove motion systems from fighter simulators. He recommended that a database of force cue requirements should be developed, a research program was needed to evaluate the benefits of various force cue devices, operational methods were needed for evaluating the contributions of force cueing systems, and flight test programs were needed to document pilot performance in the aircraft. Heintzman et al. recommended that the need for force cueing in combat flight training systems be determined on the basis of the assumption that, if the pilot in actual flight uses force cues, then they should be reproduced in the flight simulator, cost permitting.

Heintzman et al. (1999) recommended engineering development of force cueing systems, but did not mention training processes or transfer of training. This "realism" argument is unpersuasive in this era when pilots are increasingly challenged to perform systems management tasks rather than just "stick and throttle" manual control. There is no doubt whatsoever that force cues occur in flight. The main question is whether providing force cueing in the simulator provides positive transfer of training and is cost-effective. Two secondary issues are whether force cueing contributes to similarities in manual control behavior and pilot acceptance of the simulator.

Longridge et al. (2001) summarized the results of an extensive literature review stating that simulator platform motion might improve the acceptability of the simulator, at least when pilots are aware of the motion manipulation. Also, motion seems to improve pilot performance and control behavior in the simulator, particularly for disturbance tasks and in aircraft with low dynamic stability. However, their review found no evidence that any benefits of platform motion result in training transfer to the aircraft.

Are Motion Bases Necessary to Train Specific Tasks?

Some authors have suggested that motion bases are needed for specific tasks where visual information is limited, such as landing in brownout or shipboard landing. Interviews with six qualified military helicopter pilots at the Naval Postgraduate School, led to a consensus that, if hovering at 10 ft altitude in a brownout, neither instruments nor motion cues would be sufficient to maintain a manual hover for more than a matter of seconds. A minority of the pilots claimed that, with a radar altimeter, they could maintain a hover in a large helicopter with no outside visual information. Under normal operational conditions of good visibility, holding a hover within approximately 1 ft displacement is normal. Hover requires visual information about position. The optical flow characterizing a velocity vector (change in position) becomes an error to be nulled in the closed-loop manual control task. It is highly unlikely that simulator motion cues in a flight simulator would be sufficient to support manual hover in the absence of visual information. If it can't be done in the aircraft, why should it be possible in the simulator? However, there can be training benefit from certain departures from reality, as mentioned earlier. Would learning to sustain a hover without vision in a motion simulator have positive transfer to the aircraft? This is an empirical question.

In a review of flight simulator training requirements, Semple (1980) indicated that simulator motion is beneficial for training pilots to deal with flight control in turbulence (e.g., Borlace, 1967). In addition, simulator motion has been found to be beneficial for training responses to emergency situations. Cohen (1970) found that response time to activate emergency brakes during a system failure was longer without motion cues.

Dangerous tasks and emergency procedures can be practiced and trained without risk in flight simulators. One argument for simulator motion is that it can contribute to the simulation of dangerous tasks and emergency procedures by providing disturbance cues for various failures, such as engine failure. These hypotheses are difficult, if not impossible, to evaluate empirically because transfer performance in the actual aircraft would, by definition, be dangerous. Therefore, a pseudo-transfer design is the only feasible way to accomplish this type of research. Is it possible that a simulator motion base could provide negative transfer of training in this situation? It is unclear how this question could be tested because a pseudo-

transfer design does not answer the question and transfer testing in the aircraft is high risk.

Reasons Other than Training for Motion Bases in Helicopter Simulators

In-Simulator Performance

The research literature indicates a large contrast between the effects of simulator motion on training transfer and on performance in the simulator. As reviewed above, positive ToT for motion has rarely, if ever, been found, but it is common to find that simulator motion leads to better, more precise pilot-aircraft performance **in the simulator**. This benefit of simulator motion is more likely to be found when the test subjects are experienced pilots.

One example of this type of analysis was done by Ricard and Parrish (1984), who investigated the effects of simulator platform motion and G-seat cueing on the ability of qualified Navy pilots to maintain a hover over a simulated ship. The best hover control performance was associated with the motion base condition, whereas the poorest control was associated with the fixed-base condition. Performance with the G-seat was intermediate. This outcome exemplifies the common finding that experienced pilots tend to perform better in the simulator with motion.

But the purpose of a training simulator is to train the pilot to fly the aircraft, not the simulator. In short, if performance in the simulator is the criterion, a motion base is justifiable. However, if positive ToT to the aircraft is the criterion, there are virtually no data to support the requirement of a motion base.

Handling Qualities Research

Schroeder (1999) performed a series of thorough investigations of the effect of simulator motion on pilot-vehicle performance. This research used the NASA Vertical Motion Simulator (VMS), which is one of the largest motion platforms in existence, providing approximately 60 ft vertical displacement and a 40 ft longitudinal or lateral displacement. For some flight tasks in this research, the motion provided by the VMS had a one-to-one correspondence with the visual cues to motion. Experienced NASA test pilots flew an AH-64A Apache model in the reconfigurable VMS. This series of five studies varied the available dynamic range from full motion to no motion. Four DoF were investigated: roll, yaw, lateral translation, and vertical translation. Pitch rotation and longitudinal translation were not investigated.

The results indicated that both lateral and vertical translational motion cues significantly improved pilot-vehicle performance and reduced pilot workload. The yaw and roll rotational motion cues were not as important as the lateral and the vertical translational cues. When lateral translational motion was combined with the visual system optical flow consistent with yaw, pilots believed they were rotating when, in fact, they were not. Vertical platform motion influenced pilots' estimates of

altitude. This finding casts doubt on the commonly held view that pilots in simulators estimate altitude and altitude change based solely on visual cues. Based on these findings, Schroeder (1999) recommended an alternative to the common hexapod motion platform, opting for an emphasis on translational (rather than rotational) cues.

The research by Schroeder is an important contribution to understanding the role of motion platforms in simulated helicopter flight. However, the results do not provide insight into any training benefit provided by motion platforms. As noted by Schroeder (1999, p. 63), "This report has illustrated the performance and opinion differences that arise when simulator motion is provided, but it has not shown if there is any training benefit to the use of motion."

In addition, several of the significant motion effects were found with maneuver motion as well as disturbance motion. However, Schroeder (1999) used a very large and powerful motion base and the experimental subjects were experienced NASA test pilots. The results could be quite different for a normal, less capable motion base, and for pilots who are inexperienced helicopter trainees rather than NASA test pilots.

In another experiment performed with the NASA VMS, several visual and motion characteristics were tested for their influence on a pilot's ability to perform precise landings in an autorotation (Dearing, Schroeder, Sweet, & Kaiser, 2001). Seven experienced NASA test pilots flew a representation of a UH-60A Black Hawk helicopter. Combinations of four terrain features, three terrain grids, and three motion platform displacements (none, very limited, and very large) were used in a repeated measures design. Platform motion had a small but statistically significant effect on touchdown sink rate, although all three levels of motion resulted in "adequate" performance. Post hoc tests found the "large motion" condition to be significantly different (lower touchdown vertical velocity) from the limited and the no motion conditions. The pilots also rated motion fidelity, and results were unsurprising—the large motion condition was rated as having the highest motion fidelity. The results of this research again showed that a large, well-tuned motion base, as provided by the NASA VMS, can contribute to improved performance of test pilots in the simulator and that pilots like motion bases. The results provided no input, however, to decisions about training or training effectiveness.

Pilot Preference and User Acceptance

Pilots like simulator motion. Perhaps it is more accurate to say that there is consistent evidence that pilots dislike a static, no-motion simulation.

An experiment by Caro, Jolley, Isley, and Wright (1972) reported that pilots prefer motion cues in simulation, presumably because they increase "realism." The authors also suggested that more experienced pilots might require more sophisticated motion systems because they would be capable of detecting more subtle differences from the aircraft motion.

Parrish, Houck, and Martin (1977) reported an investigation of motion in a helicopter simulator. They found that pilots performing slalom maneuvers preferred motion, but objective performance measures indicated no advantage of the motion. The reduced control activity with motion suggests that pilots modified their control strategies with motion cues, supporting their subjective preferences.

Hall (1978; cited in Burki-Cohen et al., 1998) used a moderately capable 3 DoF motion base combined with a wide (200 deg horizontal) FOV visual scene to determine how various sources of information affected pilots' ability to control a simulated Harrier aircraft. Using the Cooper-Harper scale, pilots indicated a consistent preference for motion over the no-motion condition. They rated motion as most important when the peripheral visual cues were eliminated and only instruments and motion were available.

In an analysis of airline pilot response to variations in simulator motion, Reid and Nahon (1988) used a 6 DoF synergistic hexapod motion base and several conditions of motion -- classical washout, optimal control, coordinated adaptive, and no-motion. They found little impact of motion type on pilot performance and control activity, but a strong, nearly unanimous, dislike of the no-motion condition.

An important contribution was made in an investigation of motion effects on pilot performance and preference using a B727 simulator (Bussolari et al., 1988; Lee & Bussolari, 1989). The simulator had a Level C motion base and a visual display with a moderate, 75 deg horizontal FOV. Three motion conditions were used: (1) full, 6 DoF motion; (2) a 2 DoF condition comprising vertical and lateral translational motion; (3) a "special effects" vibration condition characterized by small-amplitude (.63 cm) displacement in the vertical axis. This small-amplitude motion condition was designed to provide cues for touchdown bump, runway roughness, and buffets associated with flap, gear, and spoiler extension. These special effects were provided in the two other motion conditions as well. The results showed no differences between the three motion conditions in pilot performance, control behavior, or pilot ratings of workload, utility for training, and realism.

These results are distinct from previous research because a very limited amount of motion was found acceptable to pilots, as opposed to previous studies where pilots consistently disliked the extreme case of no-motion. This finding is consistent with an interpretation that a small amount of motion may be sufficient to contribute to immersion and presence in the simulation, supporting pilot acceptance.

These investigations of pilot preference do not provide information about training transfer. But, in decisions about whether or not to purchase, maintain, and operate a motion platform, pilot preference and acceptance of the simulator are legitimate factors to be considered, independent from training transfer.

Motion Bases for Prevention of Simulator Sickness

Since the early 1970s, researchers have suggested that simulator sickness might be reduced by simulator motion (Clark & Stewart, 1973; Puig, et al., 1978). This concept is not only simple and intuitive, but it is consistent with the major theory of motion sickness variously called sensory conflict, neural mismatch, or sensory rearrangement theory (Reason & Brand, 1975). The core of this theory is that motion sickness occurs when information from the visual, vestibular, and other sensory channels is not consistent with past experience. Anecdotal evidence in support of this theory as the basis simulator sickness is common. For example, studies of the incidence of simulator sickness in Army flight simulators mention that the consensus of instructor operators and trainees is that simulator sickness is more common when the motion base is off (Gower & Fowlkes, 1989; Gower, Fowlkes, & Baltzley, 1989).

Despite the theory and the anecdotal evidence, neither survey data nor empirical data support the hypothesis that motion bases prevent simulator sickness. In a survey of 10 different types of flight simulators and over 1,000 flights, symptoms of simulator sickness were found in 10-60% of the pilots across all 10 of the simulators, both fixed-base and motion-base (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989).

As mentioned earlier in this report, Horey (1992) tested three motion conditions—full motion, restricted motion, and no-motion in a CH-53E helicopter simulator and found that the motion condition had no significant effect on simulator sickness total scores or subscale scores.

An investigation of the hypothesis that a large, well-tuned motion base would decrease simulator sickness was done by Sharkey and McCauley (1992) using the NASA VMS. Helicopter flight tasks, including a sawtooth hover pattern, were chosen because the large translational capability of the NASA VMS enabled nearly 100% of the maneuver motion displacement. Pilots were assigned randomly to the full motion group or the no motion group. Surprisingly, the level of simulator sickness was not significantly different between the motion and no-motion groups. Guidelines for the reduction of motion sickness in simulation and virtual environments were developed from this series of experiments at NASA Ames Research Center, but adding a motion base was not one of the recommendations (McCauley & Sharkey, 1992).

Other Potential Advantages of Motion Bases

Simulator motion appears to be beneficial in the evaluation of cockpit displays. In an experiment by Ince, Williges, and Roscoe (1975), the results showed that pilot evaluations of cockpit displays in a simulator corresponded more closely to evaluations in flight when the simulator motion system was on than when it was off.

Summary Arguments on Motion Bases

Virtually no empirical evidence supports the position that flight simulator motion bases contribute to transfer of training. This result has been found consistently across a range of aircraft types, missions, maneuvers, and measures. If one's perspective is that simulator features need to "earn" their way into training simulators, then motion bases have failed to do so. If one believes, like the FAA, that good training results have been obtained in the past using motion bases, so we dare not settle for anything less, then motion bases will be mandated.

Given, that simulator motion bases are inherently incapable of providing high fidelity motion representation for anything but the most benign flight maneuvers, perhaps today's highly capable visual systems provide such high quality motion cues (vection) as to render motion bases superfluous (Burki-Cohen, et al., 1998).

Roscoe (1980, p. 216) concluded that, "Complex cockpit motion, whether slightly beneficial or detrimental on balance, is not worth much; it has so little effect on training transfer that its contribution is difficult to measure at all."

On the other hand, pilots strongly prefer to have motion bases in simulators (e.g., Reid & Nahon, 1988). Although there will always be debate about what type of motion is most preferred, or what parameters of washout are preferred, there is nearly unanimous consensus that pilots dislike the "no-motion" (fixed-base) case.

Perhaps the pilot preference for motion is, in fact, a dislike of no motion. A stationary simulator is likely to work against the sense of immersion or presence. The vestibular and proprioceptive senses detect this type of extreme, quiescent state and signal a conflict with the vection induced by the visual system. Even if a small amount of motion does not contribute to training effectiveness, it may be worthwhile to avoid the extreme no-motion state by contributing to immersion, presence, and pilot acceptance. Adding a limited amount of motion, even a small amplitude vibration, as found by Bussolari et al. (1988) and Lee and Bussolari (1989) is highly likely to make a simulator more preferable to pilots. This recommendation is consistent with the suggestion by Burki-Cohen, et al. (1998) that adding vibration to a non-motion simulator may satisfy pilot preferences for motion.

Other Motion Cueing Devices

Force cueing devices, such as G-seats, G-suits, seat shakers, and helmet loaders have been used in military fixed-wing simulation to increase the realism of sustained G-loading and, sometimes, to simulate vibration situations such as turbulence, buffet, and runway rumble. These alternative force cueing devices are intended to convey sensory information to the pilot regarding acceleration cues and biomechanical events that would be associated with those events in flight. As long ago as 1978, there were attempts to integrate various force cueing features into a

single low-cost system to achieve acceleration onset cues similar to those in flight (Albery, Gum, & Kron, 1978).

Although both motion platforms and force cueing systems provide motion onset cues, there are differences between them and, ideally, they can operate synergistically. Motion platforms are limited in displacement and, therefore, are limited to providing either motion onset cues in the correct direction or more sustained changes in orientation if they are of low magnitude. Also, motion platforms stimulate both the vestibular and the proprioceptive sensory systems, whereas force cueing systems stimulate primarily the latter.

Force cueing devices can be implemented independently or as a complement to a motion platform. Although these devices are more applicable to the sustained linear acceleration found in fixed-wing fighter aircraft than in helicopters, they could be effective for dynamic flight tasks such as NOE, contour flight, and autorotation. In addition, the dynamic seat can provide motion cues in vertical acceleration maneuvers such as mask/un-mask and landing.

Research Program to Support Simulator Decisions

An ongoing program of research on training effectiveness is essential to support continued improvement of training effectiveness and efficiency. Listed below are recommended research issues and possible approaches.

1. Determine whether replicating noise and vibration cues in the simulator can provide effective training while promoting user acceptance in initial entry rotary wing training. Analyze motion conditions including the full hexapod, a "special effects" vibration of less then 1 cm displacement, and a no-motion condition. Ideally, both pseudo-transfer and ToT designs should be implemented. Both disturbance cues and maneuvering cues should be included in the selection of the tasks and maneuvers. Criterion measures would include: (a) performance in the simulator; (b) pseudo-transfer performance; (c) transfer to the aircraft; (d) opinion survey of trainees and instructors to assess the sense of presence, realism, and overall preference.

2. Evaluate the benefit of dynamic seats, either independently, or in conjunction with #1 above.

3. Compare the contribution of motion conditions and other force cueing devices to the training of specific tasks focusing on disturbance cues, as in loss of tail rotor emergency procedures.

4. Apply the basic research paradigm in #1 above at different stages of training to test whether the level of pilot experience influences the outcome.

5. Apply the backward-transfer approach (Cross & Gainer, 1987; Stewart, 1994) to investigate the transfer between aircraft and simulator for various motion conditions.

Instructional Design is the Key to Successful Training

Simulators do not train. They are tools used by good instructors to achieve training objectives. Motion is but one of many technological components of a flight simulator for training. Quality instructional design, when implemented by quality instructors, will result in positive transfer of training. Contrary to the opinion of many simulator engineers and operational personnel, realism is not "the answer" and there is no certainty that the price of a simulator is related to the training benefits received.

As noted by Caro (1979, p. 500), "Whether motion (or any other dimension of simulation) is needed in order to achieve a particular training objective remains an empirical question. However, empiricism must build upon logical analyses that establish the relationships to be tested."

Advances in intelligent tutoring systems show promise for performing some instructor tasks. This approach has been investigated for application in a UH-1 simulator for Army helicopter training (Mulgund, Asdigha, Zacharias, Krishnakumar, & Dohme, 1995; Stewart & Dohme, 2005).

Research on training effectiveness has shown that how a simulator is used is more important than specific training technologies (Salas, Bowers, & Rhodenizer, 1998). Issues such as instructional design, procedural fidelity, and visual system fidelity are likely to have much more influence on training effectiveness than whether or not the simulator has a motion base.

A Perceptual Control Theory Perspective

An alternative approach to determining what information provides training value derives from cybernetics and negative feedback control systems (Taylor, 1999). Perceptual Control Theory (PCT; Powers, 1973; 1989) and more generally, control theory applied to human behavior (Jagacinski & Flach, 2003; Riccio & McDonald, 1998) provides not only a framework but an approach to analyzing human behavior to determine what perceptual information must be available to the operator to enable control in the task. One of the basic tenets of PCT is that the fundamental perception-action loop requires a reference value, which is the perceptual equivalent of an objective or intention. The reference value provides a specification for the desired state of the perceptual information that is under control—information known as the "controlled variable." The reference value tells when the controlled variable is being maintained successfully within limits. Or, to say it another way, reference values represent what the operator would perceive when a task is being done successfully.
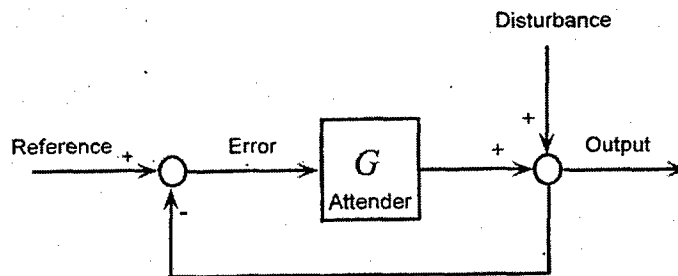
Figure 3. Simple closed-loop model; note Reference input (from Jagacinski & Flach, 2003).

For example, if a helicopter pilot in a hover were told to perform a hovering right turn of 90 degrees, the pilot would introduce right pedal and other appropriate control changes to maintain altitude and position over the terrain while yawing to the right. The key question is—what does the pilot do to perceive if/when the task is completed? In this case, he/she monitors the terrain and possibly glances at the instruments to determine heading. When he or she is approaching approximately 90 degrees right—the reference value for the perception of orientation—the pilot will reduce the yaw rate to zero. When the pilot perceives visually that the new orientation matches the reference value, the task is complete. A visual criterion is the definition of the end state and visual information is being sampled during the maneuver until the difference between current status of a visual perception and the reference value becomes null.

In this example, other sensory information was available, such as a rotational velocity, perceived by vestibular and proprioceptive senses, haptic feedback from the feel of the controls, and perhaps changes in sound and vibration associated with engine, blades, and so on. These information sources could be considered inside control loops with their own reference values. But it was the visual information that confirmed when the reference value for this task was attained: 90 degree right hover turn. If the pilot attempted to perform this simple maneuver based on the non-visual feedback information, he would be profoundly unsuccessful. What does this say about the information that is essential in a flight simulator for training?

PCT, more than other applications of control theory, emphasizes the fact that many control systems can successfully operate simultaneously. Marken (2001) gives an example of two independent control systems controlling two different perceptual variables (vertical velocity and lateral displacement) simultaneously without conflict. An entire flight scenario could be broken into a hierarchical set of closed-loop control tasks and the perceptual state associated with the reference value of each task could be identified.

Figure 4 provides another example of a closed-loop control system. This one shows the reference signal "r" as the goal, intention, or criterion for the level of the perceptual variable (the "Percep Signal" in the diagram) that is to be achieved. Note

that environmental disturbance is another input that influences the state of the perceptual variable. The system varies its outputs (Output Var) so as to compensate for such disturbances and maintain the perceptual variable at the specified reference value (the value of r).
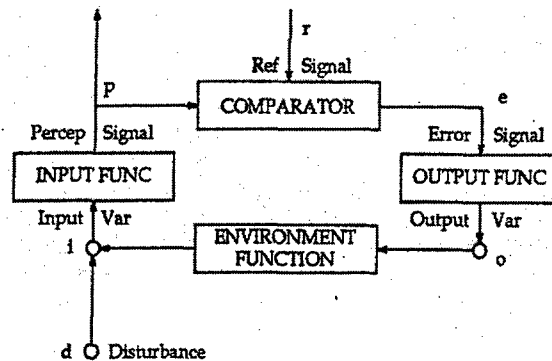

Figure 4. Another control loop example, "r" is the Reference Signal (from Powers, 1989).

Figure 5, derived from Schroeder (1999), shows a control loop for a flight simulator. The reference value is implied in the "Task demands" input arrow. The question is: What is the sequence of task demands? For example, does a pilot set references for the control of all three of the perceptual variables shown in the figure (stick displacement, motion cues, and visual cues)? Do all pilots control the same perceptual variables? Do all pilots set the same references for these variables? How does training affect the variables controlled by the pilot?
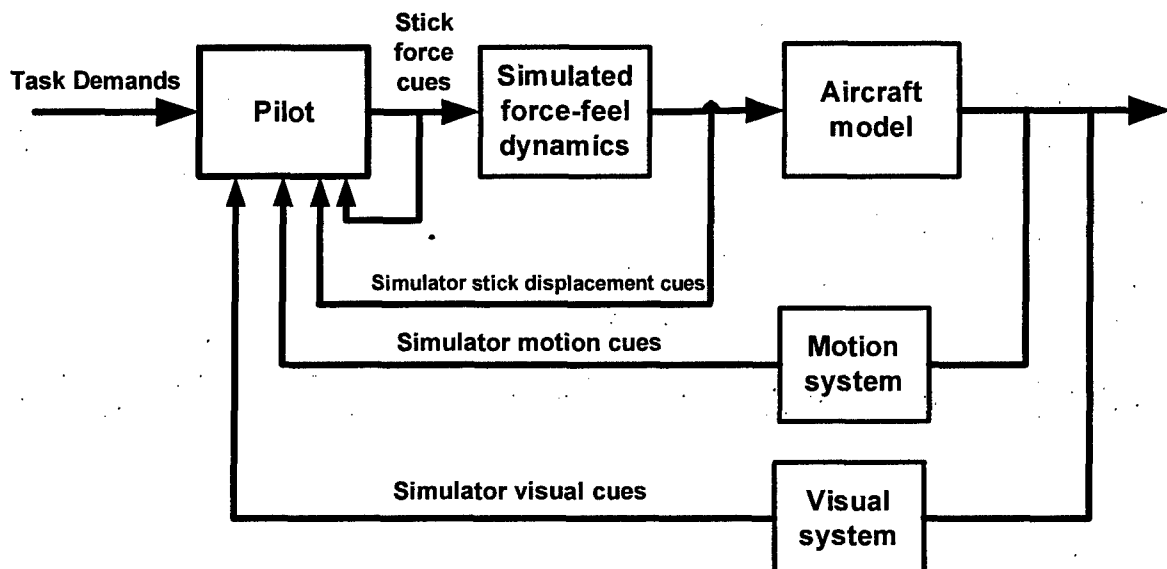

Figure 5. Control loop for a flight simulator (derived from Schroeder, 1999).

Because pilots rely on visual information for nearly all flight tasks, accurate representation of the visual world, both inside and outside the aircraft, is essential in a training simulator. A simulator motion base plus the force feedback of controls (cyclic, collective, pedals) may provide only secondary feedback in the sense that it is used by perceptual systems that run in parallel to those controlling visual variables. So control of non-visual variables may allow for some redundancy in control, which may lead to improved control performance in the motion base simulator. This concept is consistent with the work of Hess (1990, p. 482) who said that, "human fundamental compensation for the vehicle dynamics in the primary control loop are not created by motion feedback. Motion feedback merely serves to "tune" the pilot/vehicle dynamics to improve tracking performance by decreasing the high-frequency phase lags... after the fundamental pilot compensation occurs."

If one reads the literature pertaining to all of the examples of closed-loop pilot-vehicle systems in the previous figures, it is apparent that considerable effort and impressive progress has been made through the mathematical and engineering description of the control loop dynamics of the control processes involved in piloting. It is also apparent that very little focus has been given to the sequence of reference values that occur over the duration of a flight scenario. Probably one reason for this knowledge gap is that engineering analyses are more tractable than determining cognitive states pertinent to "intentions" represented as reference values.

An important part of flight training is to learn procedures, which involves learning the perceptions and the sequence of reference values for those perceptions that enable the pilot to accomplish the tasks in an acceptable manner. The trainee must learn many things including:

- What is the mission (the highest level reference value, which specifies what the perception of a successful mission "looks like")?
- What are the mission segments (the next level down; the sequence of reference specifications for the perceptions that make up "the mission")?
- What are the tasks and maneuvers (still more detailed reference specifications for the perceptions that make up the tasks and maneuvers that accomplish mission segments)?
- What are the perceptual and reference values for control loops involved in all the tasks and maneuvers that comprise the mission?
- How do trainees organize their control systems so that they can act to counter disturbances and bring their perceptions to the required reference values?

More work is needed on the definition and analysis of the perceptual and reference values involved in performing pilot tasks in order to determine the degree of simulator fidelity required to appropriately train pilots to carry out their missions. Key aspects of this analysis will be to determine the perceptual variables that pilots

actually control (Marken, 2005) and the sequence of reference values that must be set to accomplish a task.

Determining reference values and corresponding perceptual variables that define the task demands for flying will inform the selection of necessary flight simulator features as well as the development of instructional design. Research aimed at identifying sequences of reference values that are used to carry out tasks can inform the development of learning objectives. Hendy and Ho (1998), for example, applied PCT concepts to identify the "goal setting" sequences carried out by C-130 crews. The result was a set of learning objectives described in terms of a sequence of perceptual goals the crew had to learn to achieve. Clearly, however, a pilot trainee needs to learn more than just the sequence of goals (reference values) to adopt in order to carry out specific flight maneuvers. The trainee also must learn the plant dynamics and control strategies that enable him/her to achieve each of these goals while countering environmental disturbances.

The analysis of flying tasks into a series of reference values for perceptual end states offers an innovative approach to accomplishing effective training by defining what sources of perceptual information are essential to the training process.

Conclusions

- There is a substantial body of scientific data to support the training effectiveness of flight simulation. Flight simulators are unquestionably valuable for accomplishing training safely.

- There is virtually no scientific evidence to support the training effectiveness of motion platforms.

- Motion contributes to in-simulator performance, particularly for experienced pilots.

- It is possible that motion cues may be beneficial for flight training in unstable aircraft and tasks involving disturbance cues, although the evidence is weak.

- Motion, noise, and vibration contribute to the realism, sense of presence, and pilot acceptance of a simulator.

- Detailed analysis is needed of the reference values in pilot-vehicle closed-loop models.
  o Flight maneuver tasks are primarily visual and have a visual reference value.
  o Pilot trainees cannot safely "close the loop" around a vestibular or proprioceptive reference value (without vision).

- There is no reliable evidence that a motion base prevents simulator sickness.

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- Instructional design is more important than physical fidelity for training effectiveness.

Recommendations

- Perform the research necessary to better understand the relationship among training effectiveness, training technology (including motion bases and other motion cueing devices), aircraft stability, pilot tasks and workload, and training objectives.

- Consider implementing limited motion and vibration (displacement less than 1 cm) to gain the following benefits:
    - Provide event cues (e.g., landing bump, effective translational lift)
    - Avoid the fixed-base doldrums
    - Increase pilot acceptance of the simulator

- Investigate pilot performance including traditional manual control and Perceptual Control Theory relative to various flight tasks and sources of sensory and perceptual information.

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